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AN EXPERIMENTAL STUDY OF HIGH AMPLITUDE SHOCK NOISE FROM EXPLOSIVE DEPTH HARDENING

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Abstract

Explosive Depth Hardening (EDH) is an industrial process in which plastic explosives are used to compress and work-harden steel. Depending on the steel that needs hardening, the energy equivalent of up to 10 kg of TNT is used. Depending on the shipments, between one and 4 rails are hardened simultaneously. The nearest noise sensitive receptor is approximately 2 km from the source, and under specific weather conditions, EDH has the potential to exceed 130 dB(C)peak at this location. This noise source is also known to be audible and identifiable at receptors more than 10 km away.

In this study, a comprehensive measurement campaign has been undertaken to investigate the propagation of the pulse in the non-linear and linear acoustic regions. These field trial measurements were conducted in-situ on the DNV Spadeadam site during their usual daily operations. The characteristics of the blast wave, including peak pressure, shock duration, and shock speed, have been measured using piezoelectric pressure sensors.

Keywords: *impulsive noise, environmental acoustics, non-linear acoustics, industrial noise*

1. Introduction

DNV Spadeadam is a large-scale open-air scientific research and testing site located in the north of England. A common form of explosive test undertaken on the site is known as Explosive Depth Hardening (EDH), in which sections of precast high-manganese steel railway cross tracks are laid into a bed of sand, a thin layer of plastic explosive is laid on top, and detonated. The process is repeated for a second detonation. The shock waves from the explosions compress and work-harden the steel rails, which are then transported off site for prolonged use in the rail network. The tests can occur up to 10 times per day depending on the requirements and deliveries from the rail suppliers. Explosive charge weights range from 5 kg, to 10 kg per test. Although the test site is located in a remote, rural area surrounded mostly by pine forests, and wilderness, the noise produced from this process propagates for several kilometres and is clearly audible and identifiable at residential receptors up to 15 km from the source. Although the noise source complies with UK laws for noise pollution, there have been several noise complaints associated with EDH. Not only do permanent residences experience noise impacts, but the surrounding area of the site is a popular tourist destination for hiking and natural beauty.

The EDH noise source is not well understood. Studies have been conducted at long-ranges at noise sensitive receptors [1] The shape of the explosive charge follows the shape of the rail in thin rectangular shapes. Multiple rails are hardened with each detonation to increase testing efficiency. The charge weights and shapes are different for each test depending on the requirements of the testing schedule. The rail is placed in a bed of sand approximately 0.5 m from the ground. The test area sand pit has approximate dimensions of 40 m by 10 m. In the near field, these factors cause high variability in the waveform in terms of peak level, number of peaks, frequency content, and shock duration. In the far field the variability is even greater as atmospheric effects of wind speed and direction change the shock propagation. Figure 1 shows an indicative layout of rail in the test area sand pit.

Furthermore, the techniques needed to measure this noise source are unconventional. For safety reasons, personnel must stand at least 150 m from the source, based on a predicted 15 mBar overpressure limit. This means sensors closer to this must withstand extreme pressure levels. In this region the shock travels supersonically, so a higher sampling frequency is required to capture peak pressures and accurate waveforms from the blasts.

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Figure 1: indicative layout of rails during EDH.

2. Methodology

The geometry, position, and weight of explosive charges for each test were dictated by the operational needs for EDH. 40 tests have been measured with a range of explosive charge weights between 5 kg and 10 kg TNT equivalence, and this weight could be split from 1 to 4 pieces of rail per detonation. The number of tests undertaken in this study are shown below.

Table 1: Number of blast measurements undertaken.

TNT Equivalence	Number of tests
5 kg	4
6 kg	6
7 kg	8
8 kg	10
9 kg	15
10 kg	10

Measurements were taken at 30 m, 37 m, 140 m, and 200 m from the EDH source. These distances were selected for accessibility and so the sensors will not be damaged by moving plant around the site. The first array was positioned 28 degrees from North of the source and second array was positioned 45 degrees from north. The measurements were taken using high-frequency piezoelectric pressure sensors in pencil gauge casings, an example is shown in Figure 2.
High-frequency piezoelectric pressure sensors were selected instead of traditional microphones due to the extreme intensities at the measurement distances, where most microphones, even microphones with low sensitivity, would over-range. These sensors are also robust and can be used in wet weather. The sensors were connected to a high-speed logger with a sample rate of 200 kHz. This is sufficient to capture the peak shock pressure of this kind of blast source [2]. The sensors were encased in pencil probe casings. These casings are pointed towards the blast source with the sensor on the side of the casing. This allows for the blast wave to pass over the sensor with minimal turbulence or reflections[3] .
Figure 3 shows the measurement positions of during the experiments.

Figure 2: Pencil Gauge pressure sensor

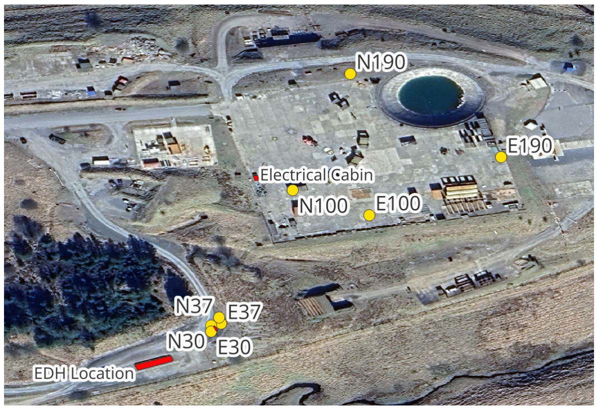

Figure 3: EDH Measurement Locations

Several variables have been considered in the source characterisation of EDH. Firstly, the charge weight of the test has been compared to the peak sound pressure levels, and impulse durations at each measurement position. This has been considered in the context of the number of charges used to make that specific explosive charge weight. As the measured shocks from the EDH source propagate, changes of peak pressure, positive phase duration, and frequency content of the impulse have been analysed.

The measurements have been compared against standard empirical predictions of spherical blast waves at the equivalent measurement distances developed by Kinney and Graham [2]. The predicted overpressure (P) at time (t) histories were calculated as Friedlander waveforms:

$$P(t) = P_s(e^{-t/t^*})(1-(t/t^*)) \tag{1}$$

Where (P_s) is the peak overpressure and (t^*) is the positive-phase duration The relationship of peak overpressure can be derived from a network equation, expressed as functions of scaled distance, Z.

$$Z = R/W^{1/3} \tag{2}$$

where R is the distance of the measurement in metres position and W the TNT-equivalent charge mass in kilograms.

$$P_s = P_a \frac{808\left[1+\left(\frac{Z}{4.5}\right)^2\right]}{\sqrt{1+\left(\frac{Z}{0.048}\right)^2}\sqrt{1+\left(\frac{Z}{0.32}\right)^2}\sqrt{1+\left(\frac{Z}{1.35}\right)^2}} \tag{3}$$

Where P_a is the atmospheric pressure [4]

Shock arrival time at each distance was predicted numerically integrating the inverse shock-front velocity as is defined by the Rankine-Hugoniot relationship.

$$t_{arrival} = \int_{R_0}^{R} \frac{dR'}{U(R')} \tag{4}$$

where $U(R')$ is the shock speed at range R' related to the pressure ratio across the front by the Rankine-Hugoniot for a normal shock in an ideal gas. $\gamma = 1.4$ for air.

Wind speed and direction were recorded using an on-site weather station positioned 360 m west-north-west from the explosive source, at a height of 4 m from the ground. The overarching wind conditions were assumed to be similar between the source and measurement positions. Wind data has been analysed as a wind projection vector, this takes into account the change in angle from north of the measurement position, and the wind direction, as well as the speed of the wind. A higher wind projection vector indicates the measurement position being in a stronger downwind position. A negative wind vector indicates the receiver position as being upwind from the source.

3. Results

During the experiments, several distinct waveforms were recorded. These are dependent on the number of rails used simultaneously per test, rather than the overall explosive weight of the test. An example of a shot with one, two, three, and four simultaneous explosions are shown in figures 4-7. These examples show similar explosive charge weights, wind speeds, and wind vectors as noted in the figures.

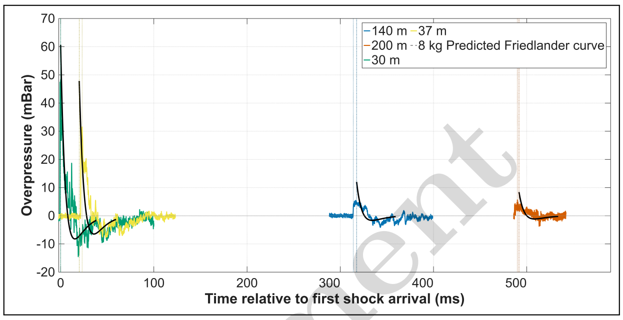

Figure 4: Wave form of 8 kg test with 1 rail and wind vector +3.7 m/s

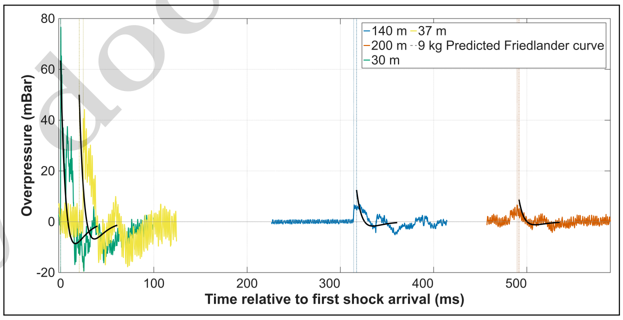

Figure 5: Wave form of 9 kg test with 2 rails and wind vector +3.6 m/s

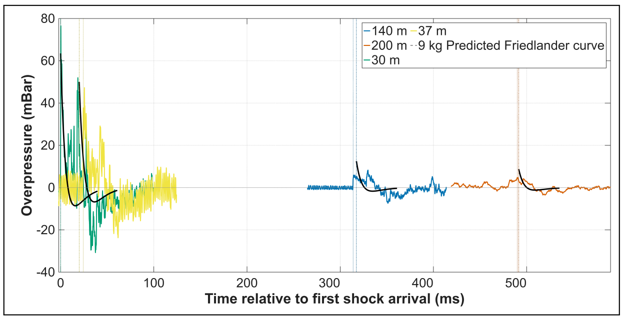

Figure 6: Wave form of 9 kg test with 3 rails and wind vector +2.2 m/s

Figues 8 - 11 show scatter plots of the measured peak over pressures at each measurement distance as compared to the wind projection vector of the tests. The data can also be shown in terms of the explosive charge weight, and number of shots per test. These are shown in Figures 12 - 15.

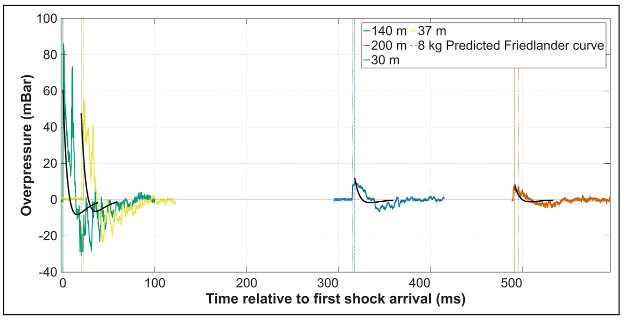

Figure 7: Wave form of 8 kg test with 4 rails and wind vector +3.7 m/s

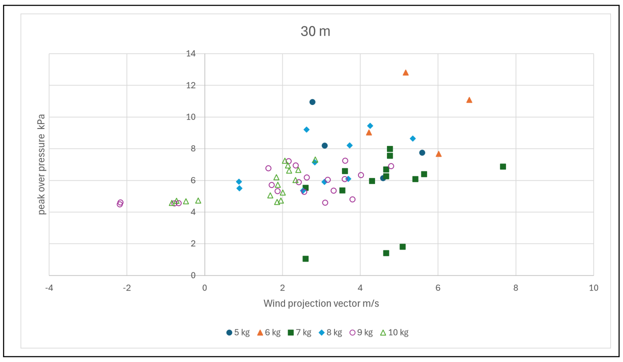

Figure 8: Peak overpressure vs wind projection when measured at 30 m

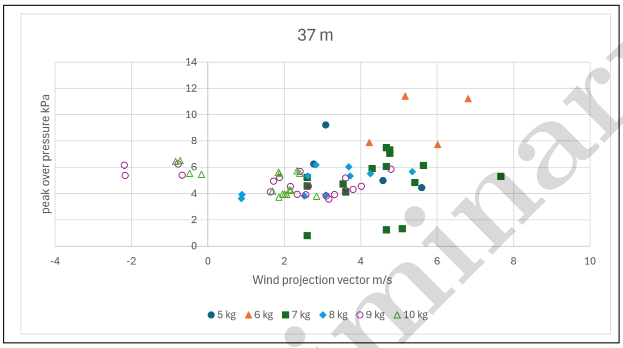

Figure 9: Peak overpressure vs wind projection when measured at 37 m

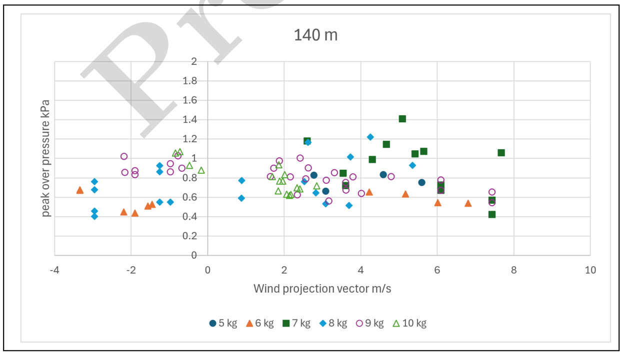

Figure 10: Peak overpressure vs wind projection when measured at 140 m

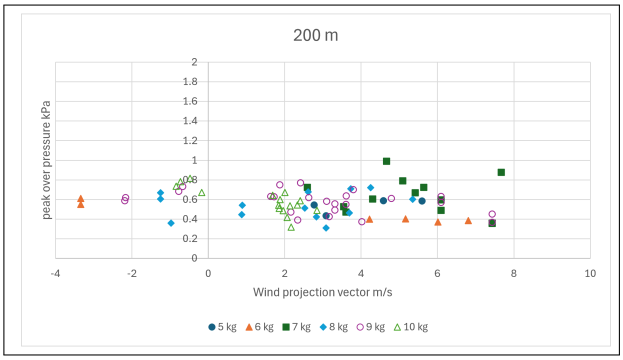

Figure 11: Peak overpressure vs wind projection when measured at 200 m

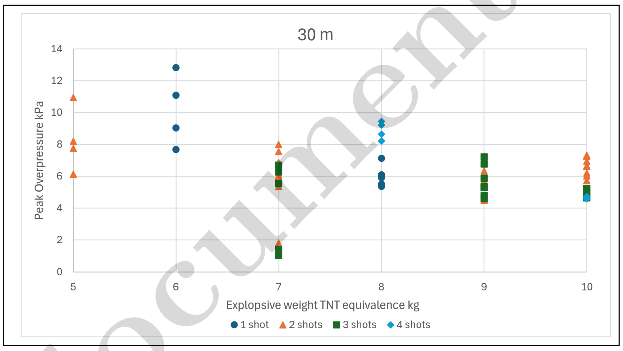

Figure 12: Peak overpressure vs explosive charge weight when measured at 30 m

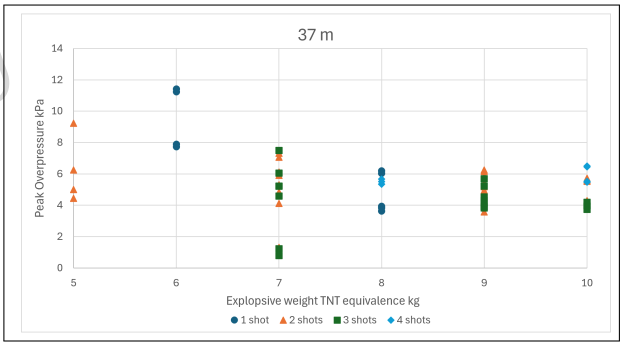

Figure 13: Peak overpressure vs explosive charge weight when measured at 37 m

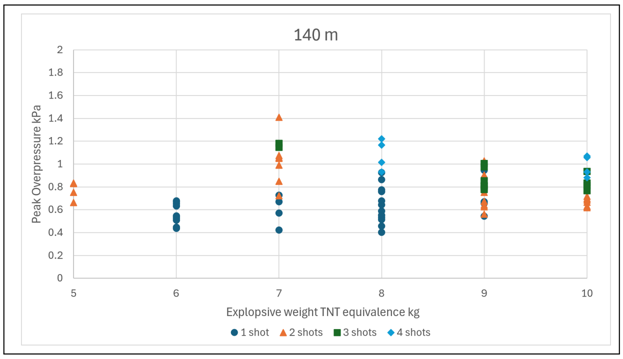

Figure 14: Peak overpressure vs explosive charge weight when measured at 140 m

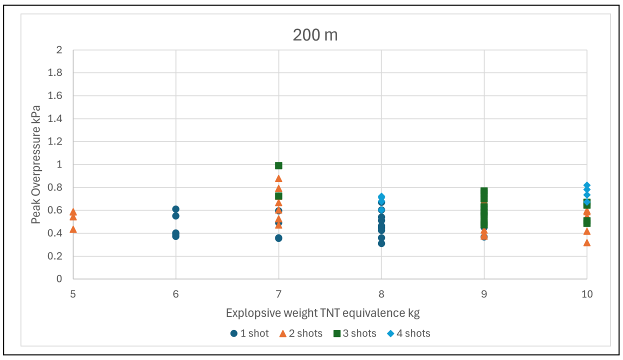

Figure 15: Peak overpressure vs explosive charge weight when measured at 200 m

Figures 16 - 19 are scatter plots of the measured impulses of the positive phase of the explosions. The impulse considers the level and duration of the impulse.

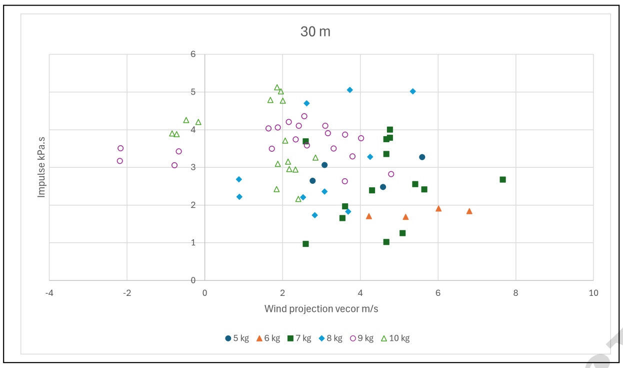

Figure 16: Impulse vs wind projection when measured at 30 m

Table 2 shows the predicted peak sound pressure level (SPL) in dB of a hemispherical blast source as per equations 2 and 3 to the nearest dB. It compares this to the average of measured peak EDH levels for the 8 kg and 9 kg explosive weight scenarios.

Table 2: Peak Sound pressure levels of EDH source, dB.

Range m	8 kg TNT		9 kg TNT	
	Predicted Peak SPL dB	Measured Peak SPL dB	Predicted Peak SPL dB	Measured Peak SPL dB
30	170	171	170	169
37	168	168	168	167
140	156	151	156	152
200	153	148	153	149

4. Discussion

Reviewing the time-pressure plots of the tests, shown in figures 4-7, in the near field at 30 and 37 m, the number of shots per test generally correlates to the number of peaks detectable in the plots. In some measurements, however, more peaks are observed than

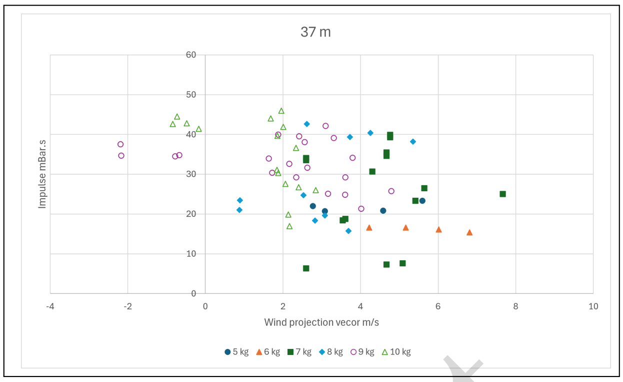

Figure 17: Impulse vs wind projection when measured at 37 m

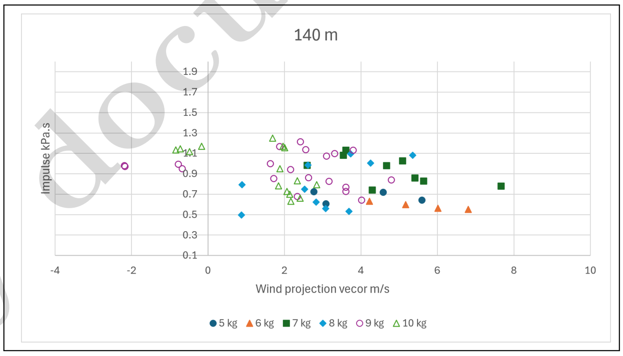

Figure 18: Impulse vs wind projection when measured at 140 m

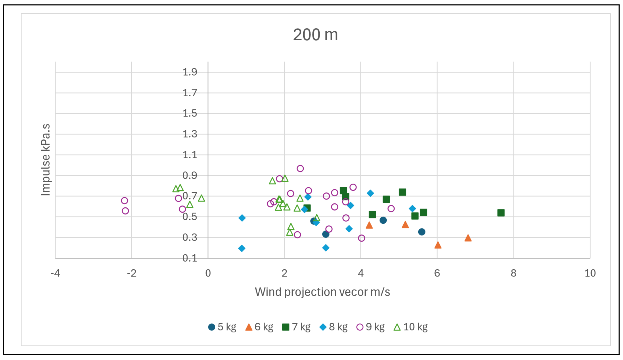

Figure 19: Impulse vs wind projection when measured at 200 m

the number of rails in the test. These are more common during tests with higher explosive weights where the explosive charge is spread in a longer distance. When this is observed, the source appears to a ct more like a line source than a point source, in which shock fronts are formed on the ends as well as the sides of the source. However, in this region under such high acoustic intensities, there are observable non-linear effects such as viscous losses. [3]. Table 2 shows that the average measured peak overpressure between sensors at these distances correlates closely with the predicted value, varying less than 2 dB from the modelled results.

At close range, the peak overpressures, and impulses had high variability both when comparing explosive charge weight and wind vector. At close range as the variability is dominated by the source itself [2]. The peak is more closely correlated with the number of rails per test than the explosive weight of the test. This was observed in the time-pressure traces where the second shock to arrive was higher in amplitude than the initial peak as the two peaks superimpose.

In the middle range, between 37 m and 140 m, the data shows that there are larger than expected losses in peak sound pressure levels; This can be speculated to be from the interaction of the source and the ground between the two measurement points. Between these positions is uneven dirt ground, with a deep valley containing an access road. Unfortunately, measurements could not be taken in between due to access requirements. This region also contains the majority of the non-linear propagation, in which losses are expected to be more than conventional acoustic wave propagation as the shock slows. This area is also very uneven with a large valley and a combination of soft and hard ground. Future work will consider the changes in ground elevation and characteristics on the shock path to quantify this.

At far ranges, over 130 m from the source, the waveforms show as weak shocks. The multiple peaks shown at close range have superimposed, forming singular shock fronts. This occurs as the shocks behind the leading shock front propagate through the more dense medium at faster speeds. At this range the wind vector has a correlation with peak overpressure and impulse metrics. As the wind vector increases, the peak overpressure increases, and the impulse decreases. This is also expected, as with higher peak overpressure, the shock width of the positive phase is less.[2]. The mean reduction in peak pressure between 140 m and 200 m is approximately half of what would be expected from a spherical point source, approximating to a 3 dB reduction per doubling of distance; acting more like a line source.

At all ranges, the peak overpressures, and the time of arrival of the blasts correlate closely with the predicted Friedlander curves, although the durations are longer in the measured results than predicted. This is due to the multiple shocks formed in the EDH tests, which super impose and interact with the atmosphere and surrounding environment. Future work will focus on the geometry of the explosive source, and the number of shots per test to quantify these differences.

These measurements have characterised the variability in the peak sound pressure levels of EDH noise source from the differences in explosive weight, number of shots, and basic wind speed and direction measurements. Future tests will incorporate a wider angle of measurement positions around the source. More measurement positions between the near field and far field are also needed to better determine the source directivity, and propagation profiles.

5. Conclusion

This paper reports comprehensive measurement campaign of the Explosive Depth Hardening noise source. 40 EDH tests have been measured with TNT equivalent weights ranging from 5 kg to 10kg. A range of simultaneous explosions were included in these weights from 1 to 4 pieces of rail per detonation referred to in this paper as "shots". The wind speed and directions were considered during the measurements and the variability of the noise source has been quantified. In the near field, the measurements show approximately 6 dB loss per doubling of distance due to strong non-linear propagation effects. The predicted overpressures correlate closely with Friedlander curves calculated with the equivalent explosive charge weight, however impulse durations of the measured blasts are longer due to the geometry of the source. In the far field, the peak pressures reduce by approximately 3 dB per doubling of distance, suggesting EDH can be approximated as a line source in the linear acoustic region. Future work will include more measurement positions in the non-linear region to better understand the attenuation of sound levels as the shock propagates.

6. Acknowledgments

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